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Magnetohydrodynamics (MHD) Engineering Test Facility (ETF) 200 MWe Power Plant

(NASA-CR-165452-Vol-1) MAGNETOHYDRODYNAMICS (MHD) ENGINEERING TEST FACILITY (ETF) 200 MWe POWER PLANT. CONCEPTUAL DESIGN ENGINEERING REPORT (CDER). VOLUME 1: EXECUTIVE SUMMARY (Gilbert/Commonwealth) HC A03/MF A01 N82-12570 Unclas G3/44 08312

Conceptual Design Engineering Report (CDER)

Volume I — Executive Summary

Gilbert / Commonwealth
Engineers / Consultants

September 1981

Prepared for
National Aeronautics and Space Administration
Lewis Research Center
Under Contract DEN 3-224

for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Magnetohydrodynamics

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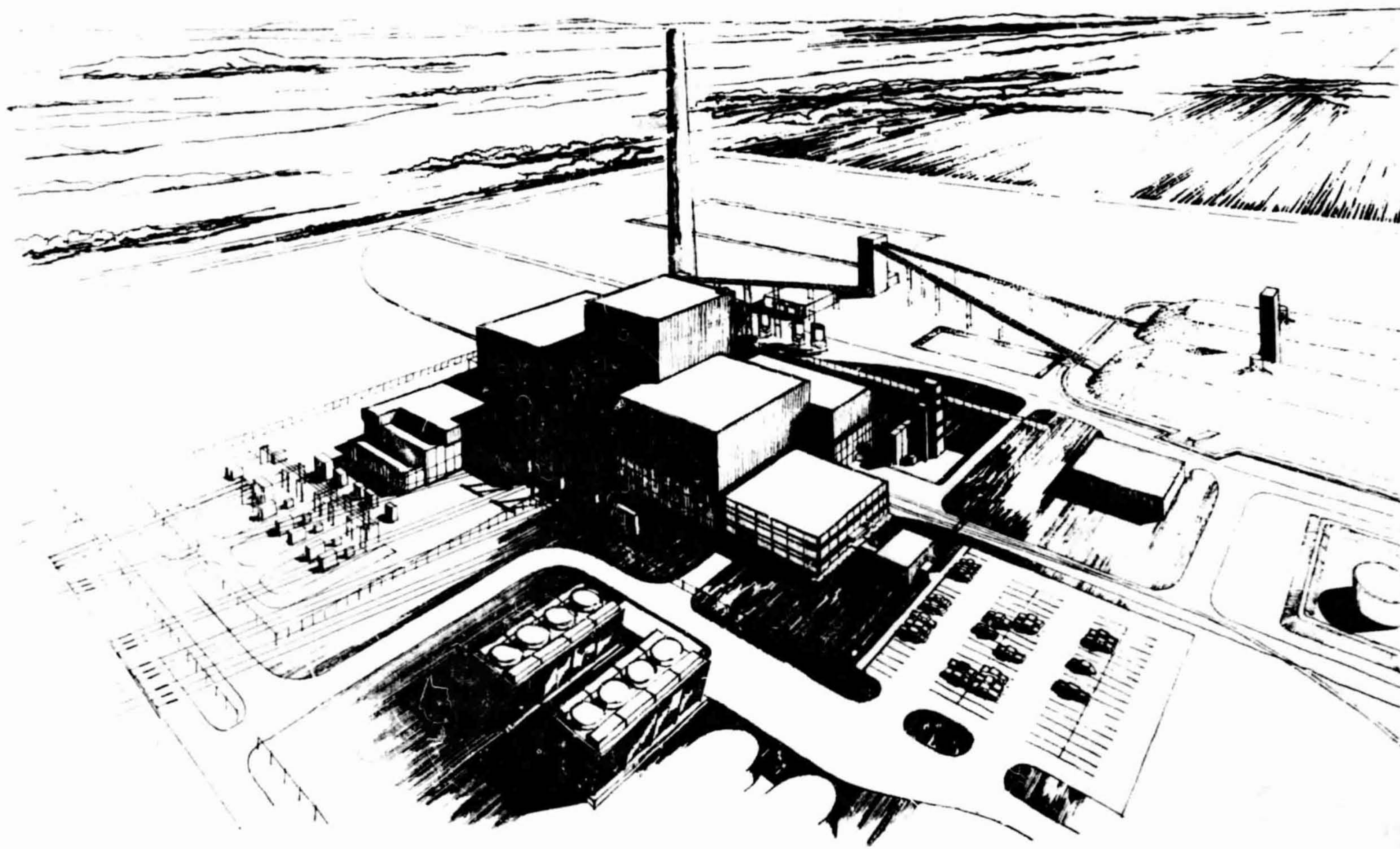
1.0 EXECUTIVE SUMMARY

This section describes the purpose and scope of the Conceptual Design Engineering Report (CDER), with a summary description of design criteria, operating parameters, plant facilities, subsystem functions, plant services, capital cost estimates, schedules, and a definition of issues requiring further clarification.

Figures 1-1, 1-2, and 1-3 present perspectives of the MHD-ETF plant and are physical representations of the design contained in the CDER. Figure 1-1 views the plant from the northeast, depicting the principal facilities from a vantage point near the main plant entrance. Figure 1-2 is a view from the southeast, providing a better view of the main functional buildings, while the cutaway of Figure 1-3 depicts the MHD, boiler, and turbine generator equipment within these buildings.



MAGNETOHYDRODYNAMICS
ENGINEERING TEST FACILITY
200 MWe POWER PLANT

FIGURE 1-1
VIEW FROM NORTHEAST

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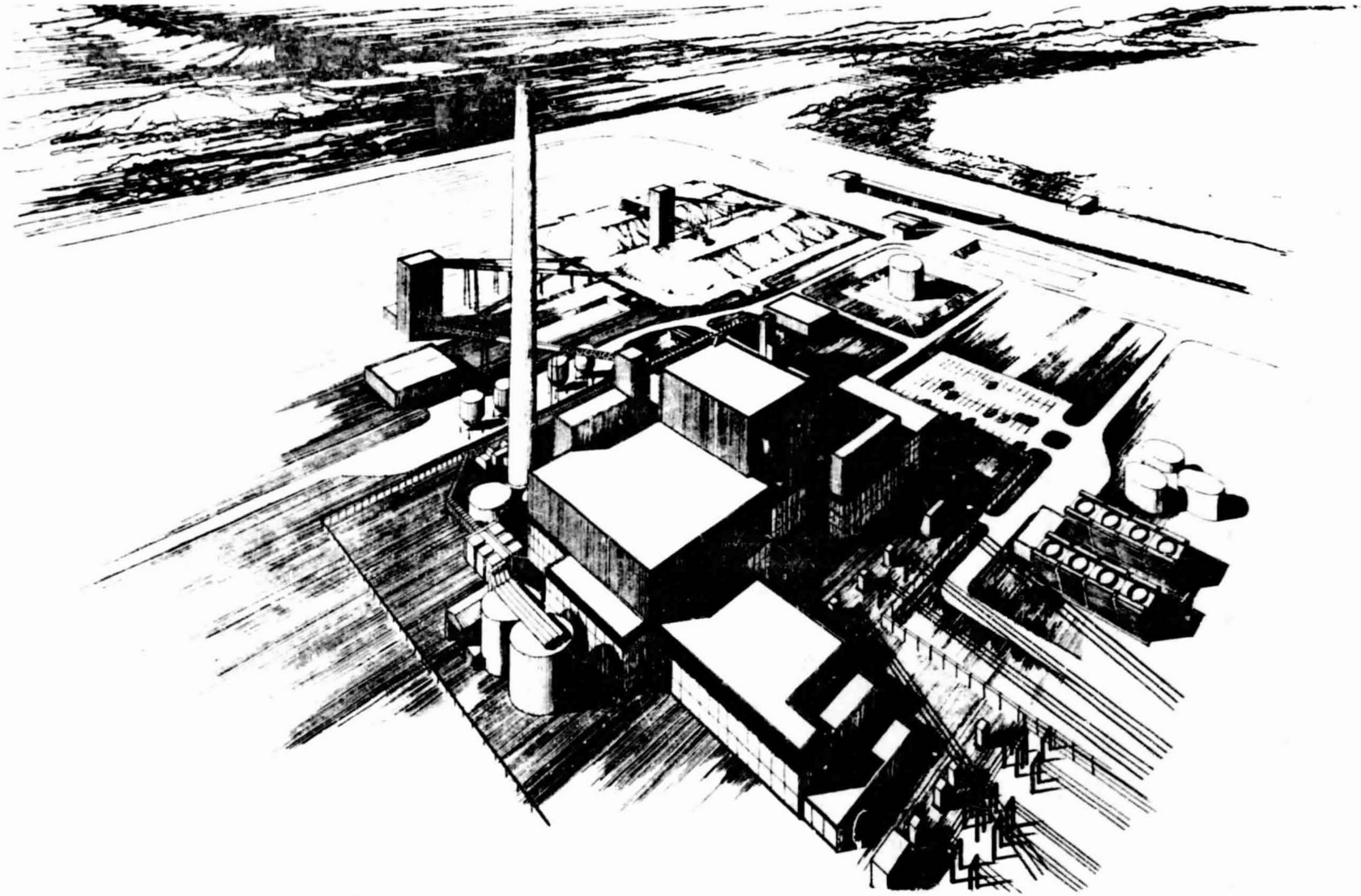
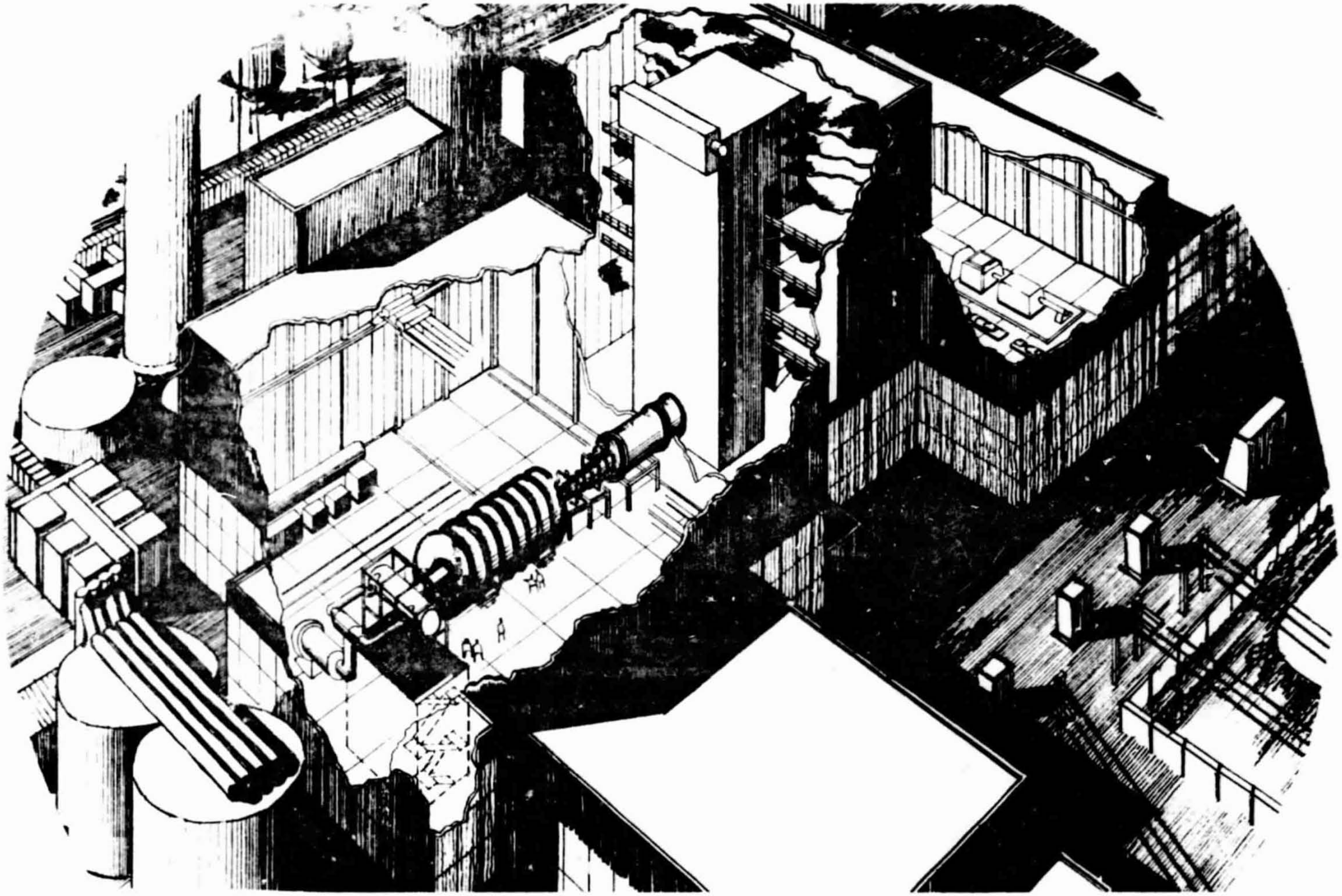


MAGNETOHYDRODYNAMICS
ENGINEERING TEST FACILITY
200 MWe PCWER PLANT

FIGURE 1-2
VIEW FROM SOUTHEAST



MAGNETOHYDRODYNAMICS
ENGINEERING TEST FACILITY
200 MWe POWER PLANT

FIGURE 1-3
VIEW FROM SOUTHEAST, CUTAWAY REVEALING
MHD TRAIN, HR/SR, AND TURBINE GENERATOR COMPONENTS

1.1 PURPOSE

Increased domestic generation of electric power from coal rather than oil represents an important step toward this nation's goal of reducing its foreign energy dependence. All new generation of electricity must be energy efficient, economically competitive, conserve natural resources and minimize the adverse effects on our environment. One area where new technology may be of significant benefit in achieving these goals is in the use of advanced energy conversion techniques in the burning of coal for utility applications.

The Department of Energy (DOE) is engaged in a national program for the development of coal fired magnetohydrodynmamic (MHD) power. The program objectives are:

1. To facilitate the commercialization of MHD/steam power generation systems;

2. To achieve overall plant efficiencies 50 percent higher than those of existing baseload utility plants;

3. To meet all environmental, health, and safety standards;

4. To generate electricity at low cost.

The potential of MHD to meet this objective must be demonstrated at a size that is acceptable to the electric utility industry for upward scaling to the size of new, near-term generating plants. The Engineering Test Facility (ETF) will provide this vital step in the MHD program.

The Department of Energy has authorized the MHD-ETF Project leading to the design, construction, and operation of a prototype of an early commercial MHD topping/steam bottoming plant. The supporting objectives of this project are:

1. To demonstrate and test an integrated, combined coal-fired MHD/steam system supplying power to a grid, which is prototypic of an early commercial plant;

2. To demonstrate the high availability features of the plant design;

3. To evaluate component interactions, control characteristics, and performance capabilities;

4. To demonstrate the environmental acceptability of the plant.

The Government has organized the ETF Project into the following elements:

1. System Engineering,
2. Conceptual Design,
3. Environmental and Site Studies,
4. Design and Construction,
5. Activation,
6. Operation.

The intitial task of the Conceptual Design element, the preparation of the ETF Design Requirements Document (DRD), has been completed. It included the preparation of a preliminary design concept, preliminary system design descriptions for the major systems and studies of alternatives. This Conceptual Design Engineering Report (CDER) completes the second task of the Conceptual Design element. It provides an initial conceptual design of the ETF and establishes an engineering and economic basis for the ETF project.

This CDER presents an engineering concept for the ETF that reflects the DRD and the system design descriptions. It includes the results of resolved technical and economic issues as well as definitive estimates of design and construction costs and a detailed construction schedule. Also included in the CDER is a compilation of unresolved technical and economic issues existing in the present design. Supporting material justifying the selected concepts has been included.

1.2 SCOPE

The CDER was prepared in conformance with system design and performance criteria issued to the ETF Project Office at NASA Lewis Research Center (LeRC) by DOE, and expanded in the DRD prepared by the LeRC ETF Project Office with assistance of Argonne National Laboratory (ANL), MIT/Francis Bitter National Magnet Laboratory (MIT/FBNML), and Gilbert Associates, Inc. (GAI) as the architect-engineer. For the CDER, GAI was assigned responsibility for the specification of the conventional subsystems and the integration of the entire ETF plant design. CDER descriptions of the high technology systems were abstracted from the system design descriptions (SDD) provided to GAI by the LeRC ETF Project Office.

A description of the completed plant has been provided along with the plant operating characteristics and performance capabilities. Capital costs estimates have been prepared for the subsystems and the overall plant. Allowance for funds during construction and the effects of inflation have not been included. A nominal milestone schedule and manpower loading for each phase of the ETF, from award of contract through design, procurement, construction, tests, and operation has been provided.

A system heat balance, layouts of equipment, and drawings of major plant facilities are included to augment the description of the plant and its operational procedures. Also included are descriptions of plant services, auxiliaries, maintenance, logistics, and security which complete the plant definition. Alternatives which could not be fully evaluated during this conceptual phase are reviewed and included in the supporting material. Detailed system design descriptions and electrical load and equipment lists for the ETF power plant are also included in the supporting material. Current and prior studies and analyses have also been included so that the trends leading to, and the justification for, the present ETF concept are available for reference.

The ETF CDER is consistent with the DOE MHD Engineering Development Program. It incorporates system design descriptions for the MHD Power Train, the superconducting Magnet, and the Heat Recovery and Seed Recovery (HR/SR) systems which have been prepared by the DOE MHD field centers and contractors who are responsible for their development. Compatibility of the designs was assured by requiring conformity to the ETF DRD, maintaining careful liaison throughout the design process, and preparing preliminary SDD's at the inception of the design.

The MHD Power Train design was assembled by the LeRC Project Office from component designs based on the results of the DOE MHD component development program. The generator design was prepared by LeRC by scaling of the design presented in "ETF Conceptual Design Study" (Reference DOE/FE/2614-2, June 1978), prepared by the Avco Everett Research Laboratory (AERL). Design parameters were developed in system studies performed by LeRC and confirmed by GAI. AERL provided assistance on channel construction and integration with the magnet and also with the consolidation circuitry. The combustor design was prepared by LeRC using design parameters and concepts provided by the DOE Pittsburgh Energy Technology Center (PETC) and the TRW Defense and Space

Systems Group. TRW has been developing MHD combustor technology at 20 MWt under contract to PETC. GAI provided a state-of-the-art inverter system design compatible with the channel consolidation circuitry and assisted LeRC in the design of a filter network to reduce consolidation circuitry harmonics.

The superconducting magnet design was prepared by the MIT/FBNML which is responsible for MHD magnet development.

The ETF HR/SR design was prepared by the ANL. The design is an adaptation of HR/SR designs prepared by Babcock and Wilcox (B&W) at 300 MWt and 2500 MWt. B&W provided design parameters and preliminary costing for the ETF design.

The Lotepro Corporation, a vendor of air separation plants, provided the design for the Oxidant Supply System under contract to LeRC. The design was based on earlier system studies which optimized the design for MHD applications.

Supporting data from the various contributors to the ETF conceptual design has been provided in Section 5.5 inthe form of system design descriptions (SDD). In some instances, SDD engineering design was continuing while the CDER text was being prepared, and SDD design revisions occurred after the CDER descriptions were finalized to meet the printing schedule. As a result, inconsistancies exist in some summary descriptions, figures and drawings between the CDER and SDD. These differences are minimal, however, and the CDER represents the overall ETF design as of its publication. The SDD contains the latest component or system data which is to be incorporated into the final ETF design.

Similarly, the engineering studies in Section 5.2 contain recommended design modifications. These recommendations are subject to future engineering review and approval prior to incorporation into the final ETF design. Therefore, these modifications are not reflected elsewhere in the CDER.

1.3 SUMMARY DESCRIPTION OF ETF

1.3.1 Design Criteria and Summary

The ETF is a self-sufficient, 200 MWe nominal-rated power plant consisting of a coal-fired MHD topping cycle integrated with a steam bottoming cycle. Baseload is the primary mode of operation, but it is capable of cycling and part-load (down to 75 percent of full load) operation. Peformance of the plant, under commercial power generation conditions, is expected to meet or surpass all existing utility standards for operating costs, plant availability, safety and reliability. The plant is also expected to meet or surpass all applicable federal, state and local environmental regulations.

The ETF demonstrates the commercial viability of the MHD process for the generation of power from coal. The MHD process directly produces electrical energy by the movement of an electrically conducting fluid through a magnetic field. In a coal-fired MHD power plant, the fluid consists of the gases formed by the combustion of coal.

An MHD generator essentially combines the functions of the steam turbine and electrical generator employed in a conventional system. Because the energy of the gas stream is converted directly to electrical energy, an MHD generator is, in principle, a much simpler device than the conventional turbogenerator. It has neither the highly-stressed moving parts of a turbogenerator, nor any solid parts that are not readily accessible for external cooling; thus, it can withstand much higher temperatures than conventional turbines. As a consequence of high-temperature operation, power plants incorporating MHD generators are potentially more efficient than conventional turbine power plants.

The MHD Power Train consists of the MHD generator (channel and diffuser), a coal combustor and nozzle, and an inverter. A superconducting magnet surrounding the channel provides the magnetic field needed for power generation. Coal is burned in the combustor with the pressurized oxidant to produce a high temperature gas. This gas is ionized by the addition of "seed" composed of a mixture of potassium salts. It is then accelerated by a nozzle to near sonic velocity and discharged into the MHD channel where both thermal and potential energy are used to generate direct current (dc) electrical power by the magnetohydrodynamic process. The power is collected by a set of electrodes in the channel wall, consolidated, and then inverted from dc to alternating current (ac) for transmission to the distribution network. The diffuser improves the performance of the generator by converting the kinetic energy of the high velocity gas leaving the channel into static pressure.

Coal, seed and oxidant are supplied to the MHD power train combustor by independent systems. To provide the combustion temperature which is adequate to ionize the seed, oxidant is prepared by mixing air with oxygen from an on-site Air Separation Unit (ASU) and then compressing and heating it to an intermediate temperature.

Considerable energy is contained in the MHD exhaust gas. The ETF utilizes most of it to generate steam which is used to drive a turbogenerator,

providing additional electrical power, and to drive the air- and oxidant compressors and other auxiliary equipment.

The ETF uses nonconventional processes to control emissions of sulfur and the NO_x formed during combustion. The sulfur combines preferentially with the potassium seed to form particulates which are removed from combustion gases by conventional methods. Recovered seed can be reused once it has been reprocessed to remove the sulfur, but reprocessing facilities are not included in the ETF. NO_x emissions are limited by sub-stoichiometric (fuel rich) combustion followed by a time controlled temperature reduction of the exhaust gases that allows the NO_x to reduce to a low concentration.

The ETF is designed for a hypothetical location typical of potential power plant sites in Montana. It is at an elevation of 3,300 feet where the standard temperature and pressure are 42° F and 13.0 psia. The relatively flat site has good soil properties and adequate surface water supplies.

The ETF configuration is shown schematically in Figure 1-4. The design parameters are listed in Table 1-1. A single subsonic MHD power train along with its ancillary superconducting magnet generates a large proportion of the total electric power. The remainder is generated by a conventional turbine generator using steam produced in the heat recovery-seed recovery (HR/SR) boiler by the residual energy in the MHD Power Train exhaust. The HR/SR also heats the MHD combustor oxidant, a mixture of air and oxygen, to 1,100° F. Compressors, driven by steam turbines, pressurize both the oxidant to the combustor, and the input air for an air-separation unit (ASU) that provides the oxygen. Seed reprocessing is assumed to be performed off-site in this design, but on-site capability may be added later.

TABLE 1-1

ETF SYSTEM DESIGN PARAMETERS

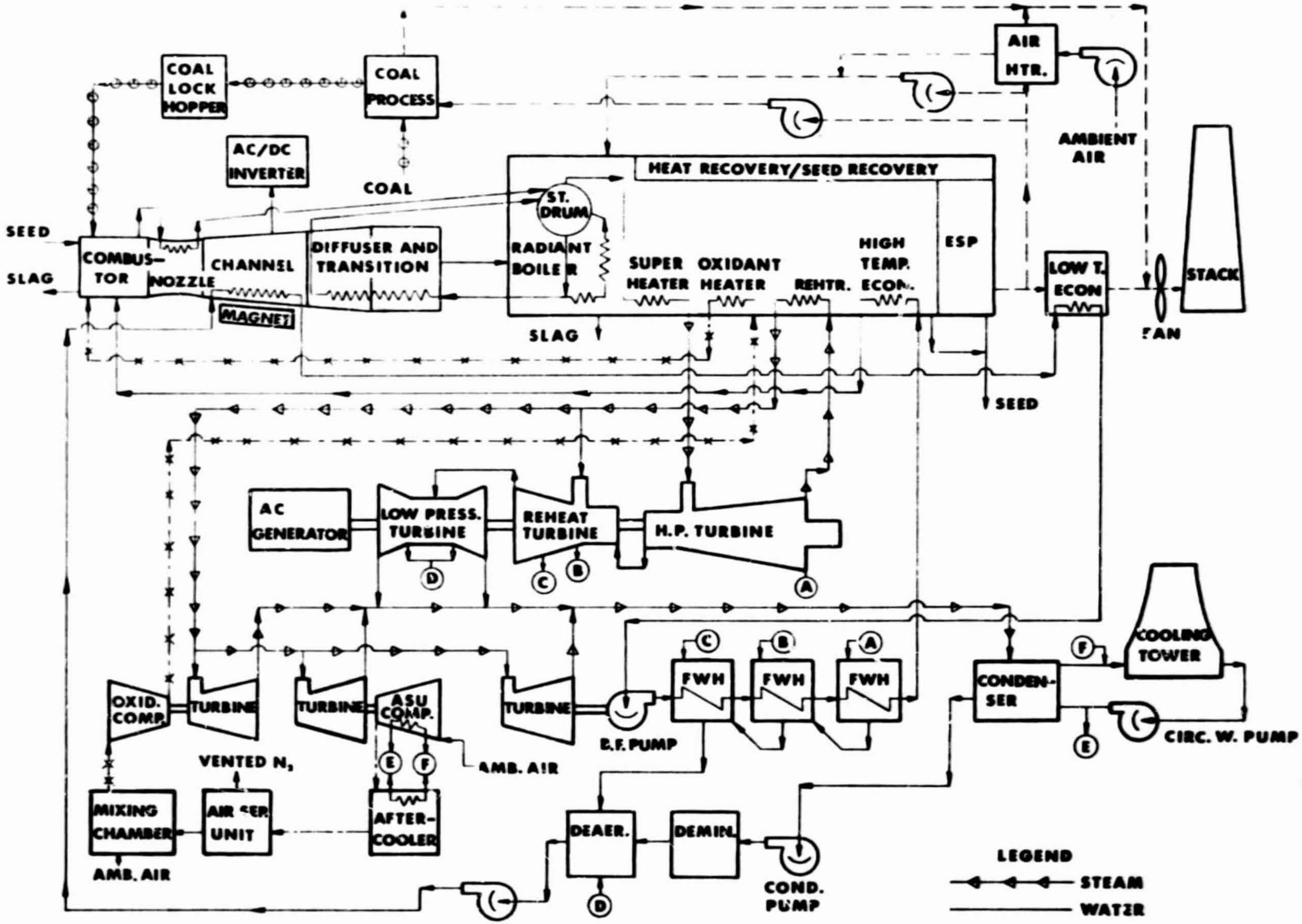
PLANT	Baseload
Power, MWe Net	202
Load range, % of rating	100 - 75
Efficiency, %	38.0
Thermal input (fuel), MWt	532
FUEL	Montana Rosebud Coal
Moisture, % as received	22.7
% as fired	5
Ash, % typical	8.7
Sulfur, % typical	0.85
HHV, Btu/lb as received	8,920
Btu/lb as fired	10,962
Size, pulverized, % through 200 mesh	70
OXIDANT	Oxygen enriched air
Oxygen content, % by volume	30
Temperature, °F	1,100
ASU efficiency, kWh/ton equivalent pure oxygen	225

TABLE 1-1 (continued)

COAL COMBUSTOR	Two stage
Air/fuel equiv. ratio	0.90
Thermal input (fuel), MWt	532
Slag rejection, % (min.)	65
Discharge pressure, psia	66.4
Discharge temperature, °F	4,380
MHD GENERATOR	Diagnally connected Faraday
Active channel length, m	12.1
L/D, inlet	19.2
Mach number, constant	0.90
Gross power output, MWe	87.1
Diffuser pressure recovery factor	0.46
Inverter type	Line commutated
Current consolidation, sources	6
MAGNET	Rectangular saddle
Peak field, tesla	6
Length, m between 4 tesla and 3.5 tesla points	12.1
HEAT & SEED RECOVERY	Radiant boiler, convection pass and ESP
Radiant boiler	Slagging
NO_x control	2.2 sec. residence above 2,900°F
Afterburner	Final air/fuel ratio - 1.05
Ash recovery, ~ %	50
Convection pass	Super heater and reheater, oxidant heater, and high temp. economizer
ESP Efficiency, % capture	99.6
STEAM POWER	Subcritical reheat
Conditions at turbine, psi/°F/°F reheat	1,815/1,000/1,000
Condenser pressure, in. Hg	2.0
Cycle efficiency, %	39.7

1.3.2 Plant Performance

The ETF Power Summary is given in Table 1-2. The MHD channel and the main steam turbine generate 87.1 MWe and 130.3 MWe gross power respectively at full load, but losses in the transformers, inverters, and generator reduce the ac electrical power output to 85 MWe and 128.0 MWe, respectively. Plant auxiliaries require an additional 10.8 MWe, leaving a net power generation of 202.2 MWe. Total steam shaft power is 168.6 MWe, including 23.4 MWe and 12.3 MWe for the oxidant and ASU compressors, respectively, and 2.6 MWe for the boiler feed pump. Plant efficiency is 38.0 percent.



SCHEMATIC DRAWING OF BASIC
ETF CONFIGURATION

FIGURE 1-4

TABLE 1-2

ETF SYSTEM POWER SUMMARY

MHD ELECTRICAL POWER: MWe	
MHD DC Power Output	87.1
Inverter/Transformer Loss	-2.1
MHD AC Electrical Power Output	85.0
STEAM CYCLE ELECTRICAL POWER: MWe	
Total Steam Shaft Power	168.6
Oxidant Compressor	-23.4
ASU Compressor	-12.3
Boiler Feed Pump	-2.6
Net Shaft Power	130.3
Turbogenerator Loss	-2.3
Electrical Power Output	128.0
GROSS PLANT ELECTRICAL OUTPUT: MWe	213.0
AUXILIARY POWER REQUIREMENTS: MWe	-10.8
NET PLANT ELECTRICAL OUTPUT: MWe	202.2

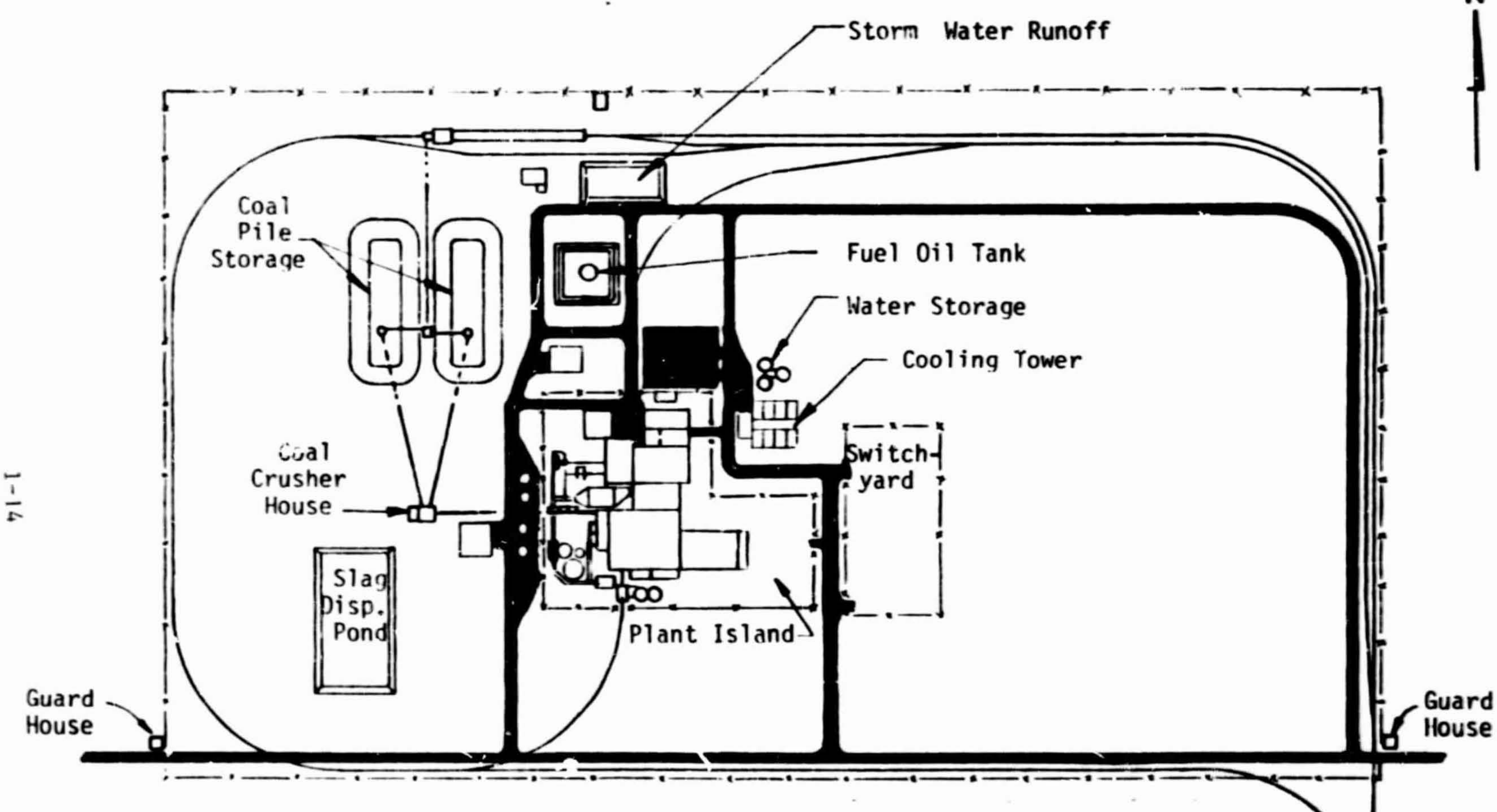
During test operation, a capacity factor of 23 percent (2,000 operating hours a year) is expected. During commerical operation, however, this factor should improve to 65 percent. Plant equipment was selected and/or designed to facilitate startups and shutdowns. Load change rates are established by components such as the steam drum and turbine and are comparable to those of conventional plants.

1.3.3 Plant Facilities Description

The ETF plant site plan and plant island are shown in Figures 1-5 and 1-6. Several major facilities are designed to meet the special requirements of an MHD/steam combined-cycle power plant.

1.3.3.1 MHD Building

The combustor, nozzle, channel, diffuser, consolidation network, and magnet assemblies are located in the MHD Building shown in Figures 1-7 and 1-8. Because high voltages and magnetic fields will be present, access to the area will be restricted during operation. Therefore, the placement of equipment and instruments will require special atttention to facilitate normal maintenance during operation periods.



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SITE PLAN

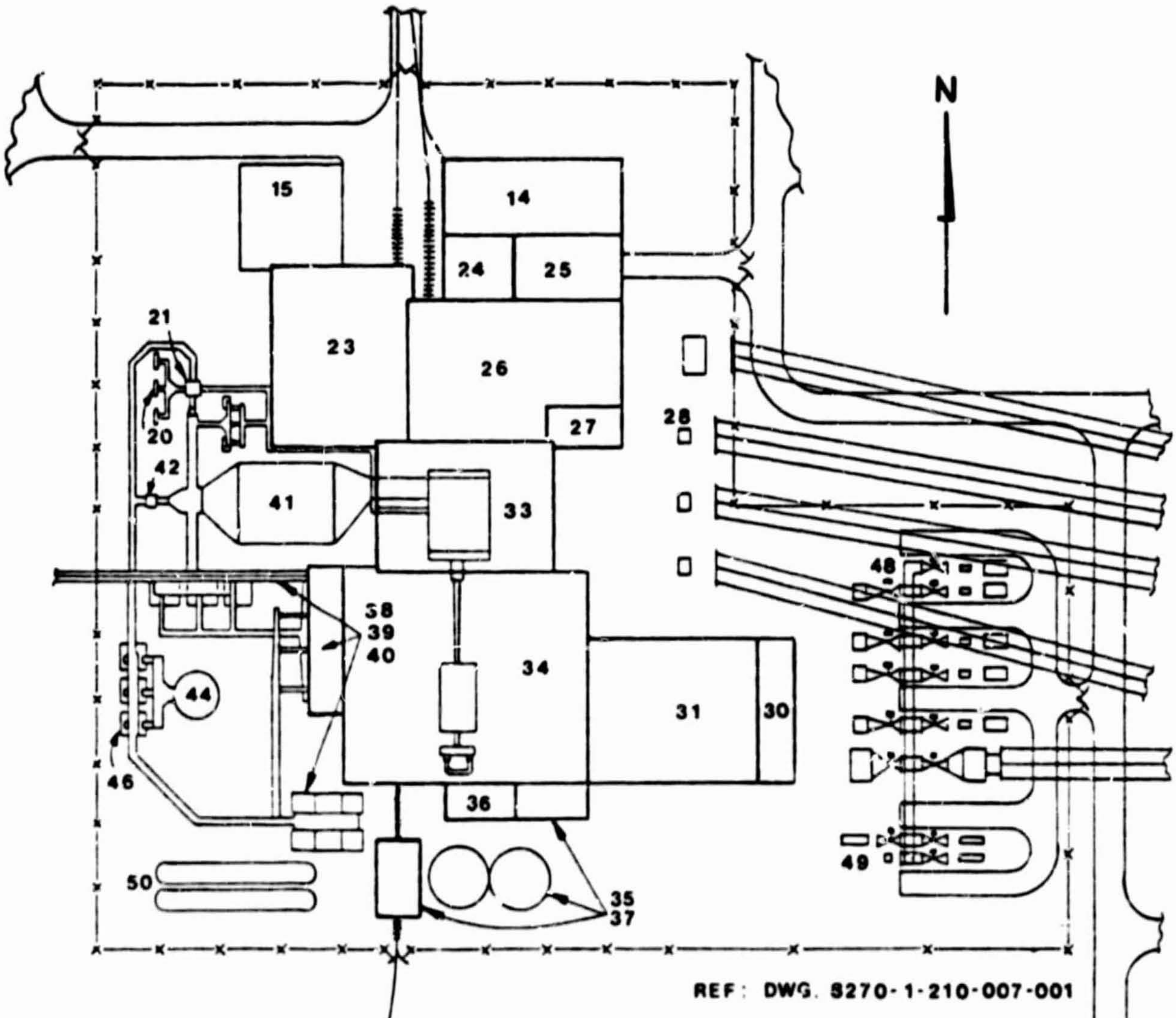
FIGURE 1-5

0 500 1000

SCALE IN FEET

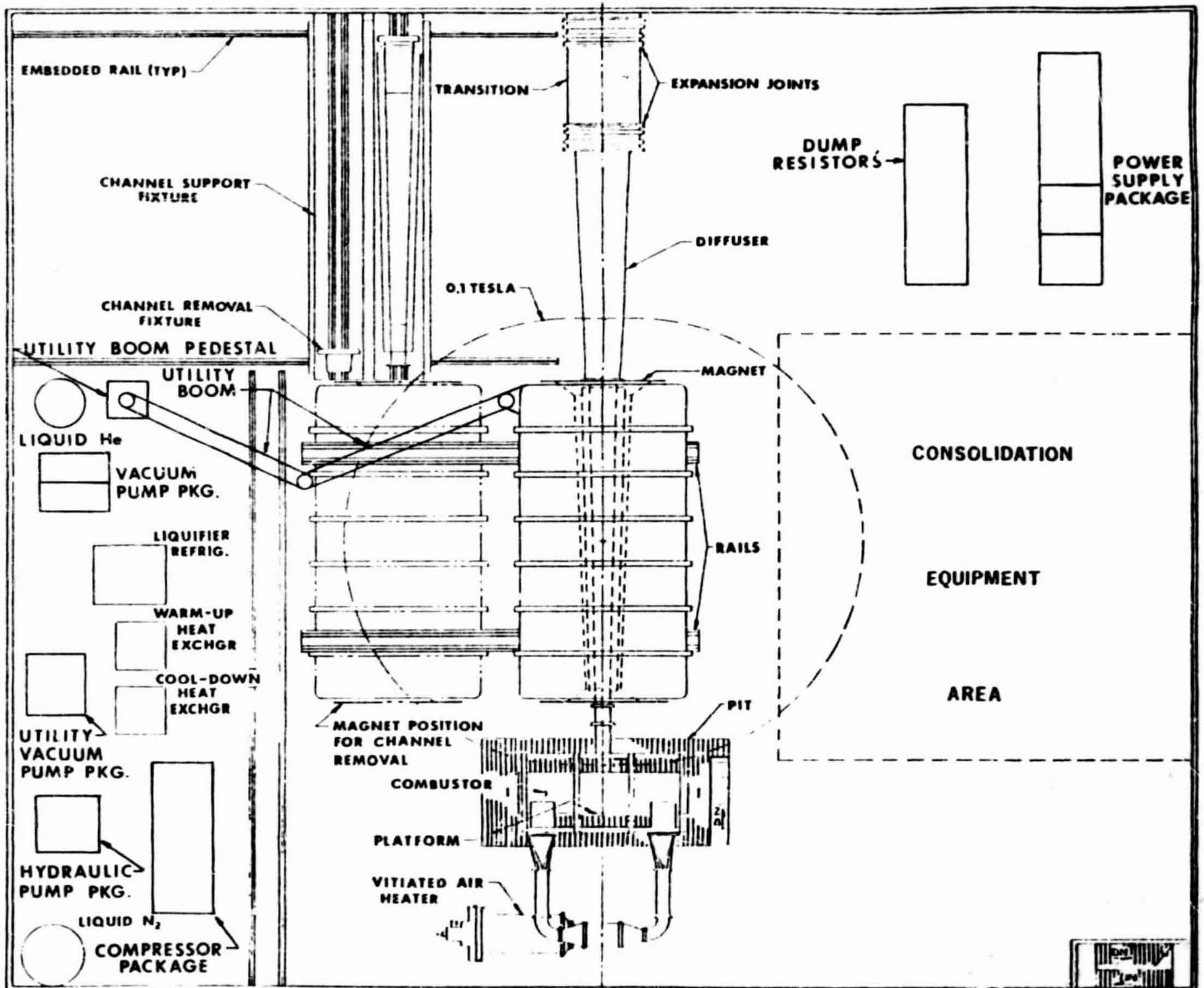
LEGEND

14 ADMINISTRATION AND MACHINE SHOP
15 AIR SEPARATION UNIT
20 AFTERBURNER GAS FANS
21 AIR HEATER
23 AIR AND OXIDANT COMPRESSOR BLDG
24 AUXILIARY BOILER
25 WATER TREATMENT AND DEMINERALIZATION BLDG
26 TURBINE-GENERATOR BLDG
27 CONTROL COMPLEX
28 TRANSFORMERS
30 SWITCHGEAR BLDG.
31 INVERTER BLDG.
33 HEAT AND SEED RECOVERY BLDG
34 MHD BLDG
35/37 SEED MGM'T
36 COAL FEED BLDG
38/39/40 COAL MGM'T
41 ELECTROSTATIC PRECIPITATOR
42 LOW TEMPERATURE ECONOMIZER
44 CHIMNEY
46 I.D. FANS
48 HARMONIC FILTERING
49 POWER FACTOR CORRECTION
50 GASEOUS HELIUM STORAGE TANKS



PLANT ISLAND

FIGURE 1-6



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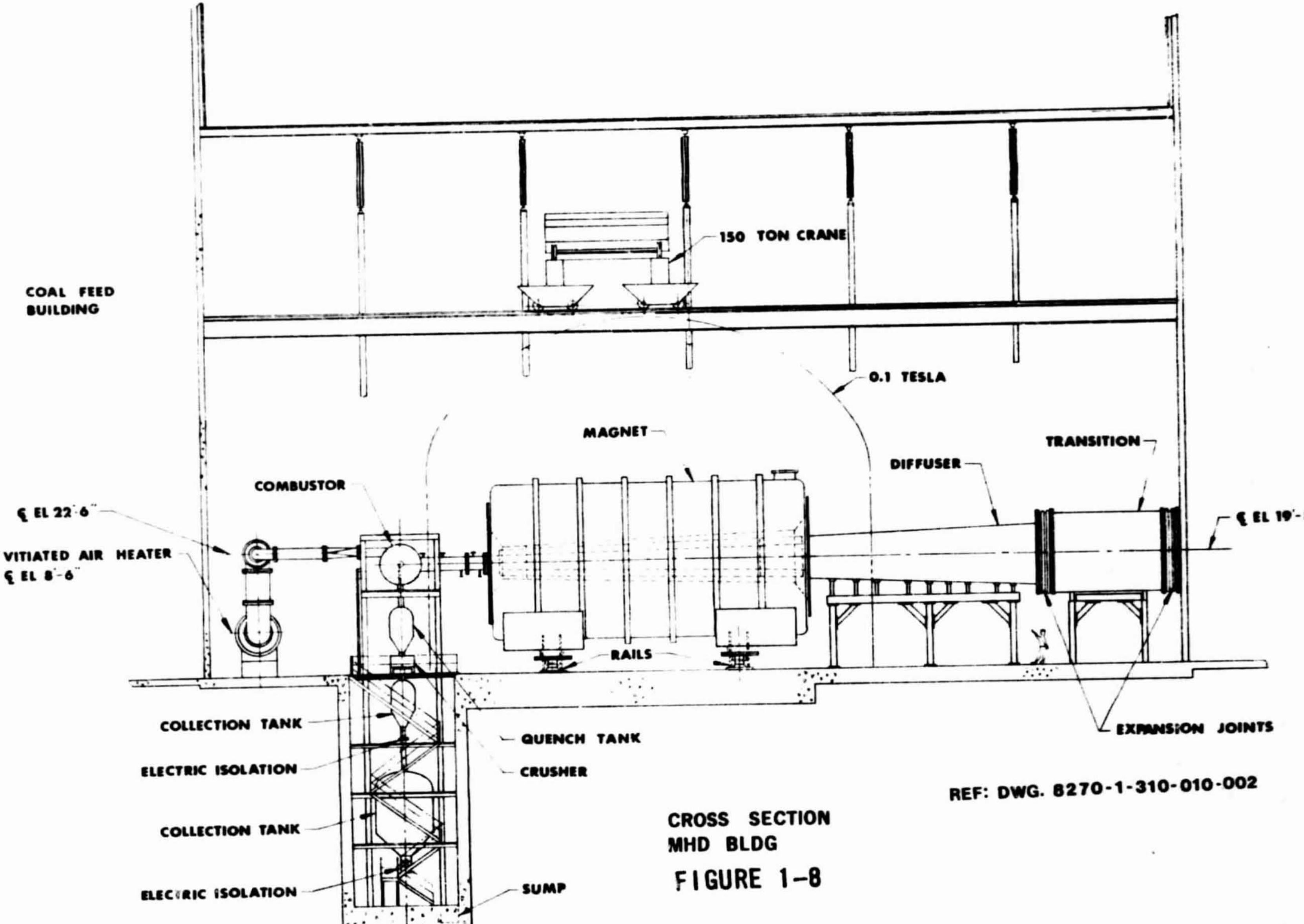
MHD BUILDING PLAN

FIGURE 1-7



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CROSS SECTION
MHD BLDG
FIGURE 1-8

Equipment and subsystems in this building are expected to be high maintenance items during the early phases of operation and require ready access. Cranes, hoists, and specialized tools and techniques will be used to minimize repair and replacement time.

1.3.3.2 Turbine Generator Building

The main power equipment of the steam bottoming cycle is located in this four-level structure. In addition to the main turbine generator, the building houses the main condenser, feedwater and booster pumps, electrical equipment, piping, cables, and the control complex. A traveling bridge crane services the turbine hall area.

1.3.3.3 HR/SR Building

This building encloses the boiler section of the HR/SR unit and provides the required access to the equipment. Normal boiler enclosure practice is followed. An electrostatic precipitator (ESP) is part of the HR/SR equipment but is not located within the building.

1.3.3.4 Air and Oxidant Compressor Building

The oxidant and air separation unit (ASU) compressors, which are located in this building, are separated by concrete shield walls. The ASU is located outdoors on an adjacent concrete slab.

1.3.3.5 Inverter Building

The inverter-bridge thyristor stacks, their smoothing reactors, and buswork are housed in this building and cooled by a forced air system. It is a high voltage hazard area. The inverter transformers and filter capacitors are located outside.

1.3.3.6 Control Complex

Operation of the plant is controlled and monitored from the main control room, which is located in the Turbine Generator Building. It is designed to provide a safe evacuation zone in the event of plant malfunctions which could endanger operating personnel.

1.3.3.7 Administration and Service Building

This building contains offices, dispensary, study rooms, training area, lavatory facilities, cafeteria, meeting rooms, storage area, janitorial facilities, and a machine shop.

1.3.3.8 Coal Handling and Preparation

Major components of the yard coal handling facilities include two 30-day compacted piles of raw coal, thawing sheds, unloading facilities, conveyors, and bulldozers to prepare and move coal. Preparation facilities include buildings for coal pulverizing, drying, and feeding.

1.3.3.9 Cooling Towers

The plant uses a cooling tower complex having eight mechanical draft, evaporative-type cooling tower cells.

1.3.3.10 Other Facilities

Other facilities include:

1. Yard Seed and Slag Handling
2. Chemical Treatment Buildings
3. Water Intake and Discharge Structures
4. Water Treatment Building
5. Storage Areas
6. Guard House
7. Machine Shops
8. Shipping and Receiving
9. Oil Storage and Pumphouse
10. Gas Turbine (Backup) Power Installation
11. Auxiliary Boiler Building

1.3.4 System Descriptions

1.3.4.1 Oxidant Supply

The system supplies pressurized oxidant, air enriched to 30 percent oxygen by volume, to the HR/SR where it is preheated en route to the MHD combustor. The oxidant is prepared by blending air with medium purity (70 percent) oxygen produced in a cryogenic ASU. Its design is nearly identical to the blast furnace oxygen enrichment system at Schwelgern, Germany, which has been operating reliably since 1973. The high efficiency of the ETF system results from the use of an ASU producing 70 percent oxygen and requiring low pressure input air, the use of an uncooled axial flow oxidant compressor instead of separate air and oxygen compressors, and the substitution of an intercooled and aftercooled axial-radial compressor to supply air to the ASU. Steam turbines power the compressors during normal operation.

Several features improve plant startup, testing, and reliability. Three 50 percent capacity oxidant compressors provide redundancy. One unit, driven by an electric motor, provides oxidant prior to the availability of steam. Also, while the plant is down, it supplies air to the ASU via a bypass, and thereby eliminates the ASU cool down period from the startup sequence. The system produces and stores liquid oxygen product for use during startup and periods of heavy demand.

1.3.4.2 MHD Power Train

The power train design is an assembly of component designs based on technology to be tested at the Component Development and Integration Facility (CDIF). The MHD generator (channel, diffuser and consolidation circuitry) is adapted from the 280 MWt ETF design prepared by AERL (its channel is a scale up of the CDIF 1A1 channel). The ETF channel is of the diagonally connected Faraday

type with barwall insulator walls. It incorporates the following modifications recommended by the AERL staff:

1. Extension of the electrode structure to regions of magnetic fields of less than 0.5 telsa to prevent electrical shorting of the Hall potential. This extends the channel to an overall length of 16 meters.

2. Reduction of electrode segmentation from 100 to 58 electrodes/meter.

3. Addition of external trusses to the primary structure.

4. Provision of current consolidation between transverse anode sements to limit fault power dissipation to approximately 1 kW.

5. Utilization of the diffuser for steam generation.

Outline diagrams and design parameters for the MHD combustor were provided by the TRW Defense and Space Systems Group, based on their development work on 20 MW combustor units. The combustor is a two-stage unit combining two first-stage combustors spiral toward each other, turn through 90° as they merge into one stream, pass through the second-stage combustor, and discharge through the nozzle to the MHD generator. The first-stage combustors gasify the coal and remove the coal ash as slag, while the second-stage completes combustion and produces the plasma. This design provides the following:

1. Relatively low heat loss and pressure drop.
2. High carbon utilization.
3. Effective slag rejection.
4. Good operational characteristics, including rapid startup and shutdown.

1.3.4.3 Magnet

The superconducting magnet provides a 6 telsa peak magnetic field with a taper toward the downstram end. Its design incorporates copper stabilized niobium titanium coils having a rectangular saddle configuration similar to that of the magnet being built by the General Electric Company for the DOE CDIF. No special windings are used to shape the field. A tapered warm bore accommodates the MHD channel, power takeoffs, and cooling lines. It is protected from a breach in the channel pressure shell by a water cooled liner. The rectangular cross section of the warm bore, using space not occupied by the coils for leads and cooling lines, permits the coil width to be determined by the size of the channel structure.

The overall magnet system is an integration of the magnet assembly, cryogenic support equipment, power supply, protection and control circuitry, and vacuum pumping equipment. The magnet is provided with tracks and rollers to enable it to be rolled 34 feet to the side to permit channel changeout.

1.3.4.4 Heat Recovery/Seed Recovery

Gas discharges from the MHD power train at about 2,200 K (3,500°F). Its energy is utilized by the HR/SR for steam generation and oxidant preheat. The

HR/SR also recovers seed and controls emissions. A schematic arrangement of the HR/SR is shown in Figure 1-9. The major components are as follows:

1. Boiler

The ETF design is basically a Carolina type boiler, which is a balanced draft, subcritical, drum type unit, comprised of a radiant boiler and a convective section which contains the superheater, reheater, economizer, and MHD oxidant heater.

a. Radiant Boiler

The radiant boiler is of conventional membrane wall construction, formed from vertical tubes placed on close centers. The radiant boiler is divided into refractory lined lower section where NO_x is reduced (at a stoichiometry of 0 .9), and a bare metal upper section. The refractory lining improves NO_x reduction by limiting the gas cooling rate, and reduces corrosion caused by the required reducing atmosphere. Air is added in the upper afterburner section to make the gas slightly oxidizing at a stoichiometry of 1.05. The slow rate of combustion along with the high heat loss to the bare metal walls prevents the temperature from rising to levels at which NO_x reforms. A slag tap at the bottom of the boiler removes 40 percent of the slag carried over from the combustor.

b. Superheater

Steam, formed in the boiler walls, is separated from the two phase mixture in the boiler drum and superheated to 1,005°F in a three section superheater. Spray attemperation prevents overheating of the steam.

c. Reheater

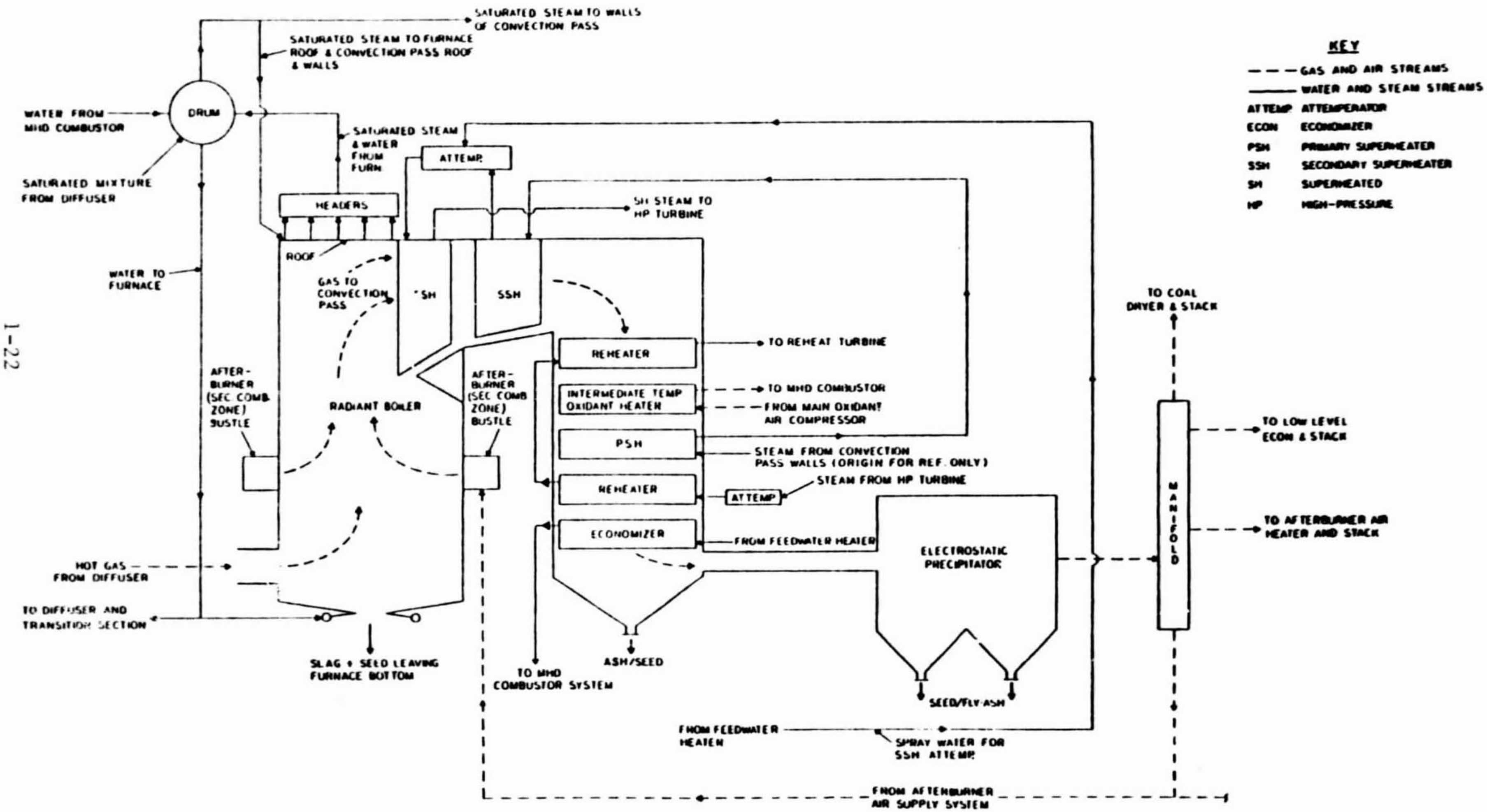
Cold reheat steam, discharged from the high pressure turbine, is piped to a two section reheater for reheat to 1,001°F. A spray attemperation unit prevents overheating of the steam.

d. Intermediate Temperature Oxidant Heater

The oxidant heater is a gas-to-gas heat exchanger which heats the oxidant discharged from the compressors to 1,100°F. During startup, heating of the oxidant is provided by an oil fired vitiation heater which also serves to preheat the HR/SR and equipment in the bottoming cycle.

e. High Temperature Economizer

The high temperature economizer heats feedwater using the MHD exhaust gases.



HEAT RECOVERY/SEED RECOVER SYSTEM

FIGURE 1-9

2. Electrostatic Precipitator (ESP)

The ESP removes 99.6 percent of the particulates (primarily seed) entrained in the gas discharged from the high temperature economizer.

1.3.4.5 Steam Power System

The steam generated in the HR/SR powers a conventional turbine generator to produce additional plant electrical power and powers turbines to drive the compressors and boiler feed pumps (BFP).

1. Main and Reheat Steam

The main steam piping conveys steam at 1,815 psi and 1,000°F to the high pressure (HP) turbine. Cold reheat steam from HP turbine exhaust is reheated to 1,001°F and directed to the intermediate pressure (IP) turbine and to the compressor and BFP turbine drives. The steam discharge from the IP turbine is expanded in the low pressure (LP) turbine and discharged to the main condenser. Attemperation in the reheater is provided by the use of feedwater from an interstage bleed on the BFP, and in the superheater by use of feedwater from the BFP discharge. The main turbine generator is rated at 128,044 kW/153 kVA and is hydrogen cooled.

2. Steam Bypass and Startup

This system bypasses the HP turbine by directing steam from the superheater header to the cold reheat header, and bypasses the IP and LP turbines by directing steam from the hot reheat header to the main condenser. Attemperation is provided for both the HP bypass steam and LP bypass steam by feedwater taken from the BFP discharge. Interlocks prevent steam bypassing if attemperating water flow is interrupted. The main condenser is protected by pressure and temperature switches that close the bypass valve during abnormal operation.

The HP bypass control valves can be regulated during cold or warm startup to control generated steam pressure. Once steam flow is established through the reheater, the turbine metal temperatures can be increased at the required rate.

3. Extraction Steam

Steam is extracted from the main turbine cycle at four points and used for feedwater heating.

4. Condensate

Exhaust steam from the LP turbine and the BFP turbine drives is condensed in the main condenser. Steam from the compressor drive turbines is condensed in individual condensers, and the condensate drains to the main condenser. Condensate is pumped from the main condenser hotwell and is utilized for cooling in the steam seal exhauster. Condensate quality is maintained by passing it through a full-flow demineralizer prior to entering a deaerating feedwater heater.

5. Boiler Feedwater

Boiler feedwater is pumped from deaerator storage to the cooling passages of the MHD channel. It then cools about one third of the gas leaving the ESP in the low temperature economizer, and after being raised to boiler pressure by the BFP, passes through three stages of feedwater heating. Finally it is used to cool the flue gas in the high temperature economizer and cool the MHD combustor before being converted to steam in the HR/SR.

6. Feedwater Heater Drips

This system maintains normal condensate levels in the feedwater heaters and controls flow of condensate to the deaerator. An important function of this system is to prevent water slug surges from entering the turbine via the extraction steam piping to the heaters.

7. Feedwater Heater and Miscellaneous Drains, Vents, and Reliefs

This system drains and vents the feedwater heaters to the main condenser, and conveys condensate from miscellaneous steam line drains to the main condenser.

8. Condenser Air Removal

Non-condensable gases are exhausted from the main and auxiliary condensers by steam jet air ejector and rotary vacuum pump systems which can be used singly or in parallel.

9. Circulating Water

This system supplies cooling water to the main and auxiliary condensers, to the compressor intercoolers and aftercoolers, and to the closed cycle heat exchangers. The returning water is cooled by the evaporative cooling towers.

1.3.4.6 Auxiliary Systems

1. Auxiliary Steam

Auxiliary boilers provide up to 200,000 pounds per hour of 115 psi, 350°F steam for plant heating and auxiliary services during plant startup and operation.

2. Boiler Flue Gas

After particulates are removed from the boiler flue gas by the ESP, the flow is split into separate streams and used for the following services:

a. Coal drying and transport
b. Coal (pressurized) injection
c. Afterburn air heating and dilution
d. Feedwater heating

One portion of the flue gas is used to dry pulverized coal to 5 percent moisture while transporting it from the pulverizers to a baghouse. Here the coal is separated from the gas stream, which is exhausted to the stack. Another portion of the flue gas is passed through a regenerative heater to heat afterburn air for the HR/SR. Part of the cooled gas leaving the air heater is compressed for use as an inert gas to pressurize the combustor coal feed lock hoppers. The remainder of the flue gas not used above is passed through a low temperature economizer feedwater heater to complete heat recovery before discharge to the stack.

3. Coal Management

During baseload operation, the ETF requires processing of 102 tons of coal per hour which is delivered by rail. There are provisions for thawing, dumping, weighing, and transporting the coal to storage bunkers. Excess coal is compacted in two 30-day capacity storage piles. Coal to be fired is transported to active storge in bunkers, weighed, and fed to the pulverizers. It is then pulverized to 70 percent through 200 mesh, dried, and transported to pressurized lockhoppers by flue gas. Pressurized flue gas then fluidizes and transports the pulverized coal through the injection lines to the combustor.

4. Seed Management

Fresh potassium carbonate seed (K_2CO_3) is delivered to the site in sealed rail cars and conveyed to a sealed storage silo. A fraction of spent seed, primarily potassium sulfate (K_2SO_4), is transported via truck to an off-site location for either seed reprocessing or disposal. The remaining fraction of spent seed is recovered from the convective section of the HR/SR and from the ESP and transported via truck to a second sealed storage silo. Measured amounts of K_2CO_3 and K_2SO_4 are transported from the storage silos through the pulverizers by an air stream. Cyclones then separate the seed from the transport air and drop the seed into pressurized lockhoppers. Seed is injected into the combustor by means of pressurized oxidant.

5. Slag Management

A maximum of 12 1/2 tons of slag per hour generated by coal combustion is expected to be removed by this system. The slag removal equipment is designed to remove 10 tons per hour of slag from the pressurized combustor, and 2 1/2 tons per hour of slag from taps in the radiant boiler.

6. Electrical

The electrical system delivers the electrical power generated by ETF to the utility grid; distributes power to the auxiliary systems for startup, shutdown, and normal operation; supplies emergency power to the ETF plant critical loads to allow an orderly emergency shutdown when normal power

is lost; and provides an uninterruptible power supply for essential plant equipment (such as computer, instrumentation, and controls (I&C)). Unit synchronization to the utility grid is automatic with manual selects.

The primary load centers of ETF are connected through a ring bus. These 138 kV load centers are, in order:

a. The MHD power train, through the inverter bus step-up transformer.

b. First utility grid line.

c. Service transformer for topping cycle auxiliary loads, and the oxidant compressor motor transformer.

d. Service transformer for bottoming plant loads, including coal management.

e. Second utility grid line.

f. Steam turbogenerator, through its step-up transformer.

The electrical system configuration ensures that power will be available from off-site during startup, shutdown, or loss of one utility line. It provides a means of starting large motors which does not reflect the voltage drop through the entire distribution sytem. It furnishes a protective relay system, which isolates and interrupts faults at all voltage levels with a minimum disturbance. Bus interconnects provide sufficient station service transformer capacity to meet the total plant power requirements even if one of the transformers fails. If power from the ring bus is lost, the critical loads are maintained by automatic start, self-synchronizing gas turbine generator units. The most essential plant equipment is serviced through a bypass by a battery-powered uninterruptible supply.

1.3.5 Plant Services

A number of conventional plant services are required to support the ETF.

1. Closed Cycle Cooling Water

   The closed cycle cooling water system circulates cooled, treated water through a closed loop system to equipment in the Turbine Generator and Compressor Buildings, the HR/SR Building, and the MHD Building. Main equipment serviced includes:

   a. Turbogenerator hydrogen and oil coolers
   b. Condensate, boiler feed pumps (BFP) and booster pumps
   c. Pulverizer mills
   d. Magnet warm-bore liner
   e. Flue gas blowers and fan bearings
   f. ASU and compressors

2. Plant Makeup Water

The cooling towers are the main users of plant makeup water, but other plant systems are also supplied. Sources for makeup are a combination of commercial supply and local groundwater and streams. Storage tanks include a 400,000 gallon unit for filtered water and fire protection water backup, and a 300,000 gallon unit for raw water.

3. Sampling

The sampling system collects and analyzes water and steam samples for their pertinent chemical characteristics. Selected samples are analyzed and their properties recorded on a continuous basis.

4. Industrial Gas

The sytem provides dry, clean and oil free plant service air and instrument air from a single header at 140 psi. Other gases such as nitrogen, helium, hydrogen, and carbon dioxide are provided for miscellaneous purposes.

5. Fuel Oil

The fuel oil system provides storage and transport of fuel oil from the unloading area to the transfer tanks and supplies fuel oil to the:

a. Auxiliary and building boilers
b. Emergency power supply and fire pump
c. Vitiation air heater (for startup only)

Oil is stored in a main 840,000 gallon storage tank, in individual under ground emergency tanks, and in day tanks.

6. Plant Industrial Waste

The plant industrial waste system collects, stores, transfers, and processes, as needed, the liquid and sanitary wastes generated throughout the plant. Resultant effluent discharges comply with governmental and industrial standards. Major sources of waste are:

a. Coal pile runoff
b. Chimney and air heater wash
c. Demineralizer regenerative wastes
d. Building drains
e. Wastewater treatment
f. Fuel oil area runoff
g. Plant yard drainage
h. Sanitary waste

Oil contamination wastes pass through reclaimer tanks. Sanitary wastes are treated in the sewage treatment area before discharge.

7. Fire Service

The fire service system provides the means to detect and combat facility fires. In addition to water, stored in two separate tanks, specialized fire suppression fluids and techniques are provided.

8. Domestic Services

The supply and maintenance of potable water and the disposal of sanitary waste are specialized functions listed separately for emphasis. They are also included under the Plant Industrial Waste and Plant Makeup Water systems.

9. Heating, Ventilating, and Air Conditioning

Services are provided for:

a. Protection against freezing of water supplies
b. Comfortable working environments
c. Dilution of odors
d. Controlled environments for temperature-humidity sensitive equipment

Major load zones included the Adminstration, Compressor, MHD, and Inverter Buildings; the Consolidation Area; and the Main Control and Relay Rooms.

1.3.6 Performance Assurance Program Plan

A performance assurance program plan incorporates and identifies the necessary reliability, safety, and quality assurance programs for the ETF project. Performance assurance activities continue from the conceptual design phase through construction, test and operation.

Main elements include:

1. Reliability

Continuous assessment of the design to meet ETF reliability, maintainability and availability objectives.

2. Safety

Identification and analysis of hazards and the means to eliminate or control these hazards to minimize risks to personnel and equipment.

3. Quality Assurance

Continuous review of technical documentation and procedures to ensure compliance with approved standards.

1.3.7 Environmental Analysis Study

The National Environmental Policy Act of 1969 makes the protection of the environment a matter of law. An environmental assessment of the ETF is required per Federal Regulation 1508.9 "Environmental Assessment". Since the ETF is the first-of-a-kind demonstration facility, a non-site-specific Environmental Analysis Study will precede the Environmental Assessment so that its determinations will be available for the Authorization phase. The study will:

1. Assess the potential impact on the environment of this new technology demonstration plant. Problem areas requiring further technological development will be identified and assessed.

2. Provide a mechanism for identifying and establishing specific design standards for those plant components and systems (and their interfacing auxiliary system performance), whose design may be controlled by national standards for protection of the environment.

1.4 PLANT COSTS

1.4.1 Costing Procedure and Bases

The cost estimate was prepared in accord with the Federal Energy Regulatory Commission (FERC) account structure, modified to provide accounts for the MHD equipment (No. 317). Indirect cost categories for "Engineering" and "Other Costs" are included using factors specified by DOE/MHD. Costs are for overnight construction and are in first quarter, 1981 dollars.

The cost of components and materials was developed from a combination of sources. Vendor data, the most accurate, were obtained from direct quotes or from current Gilbert Associates, Inc., in-house price books. Costs for the conventional sytems were compared with the analogous costs from recently costed conventional plant designs. Costs of the development systems were compared against other MHD design studies. Judgement was used to estimate costs of small items or bulk quantities such as wiring or small piping. The Plateau Region section of the "Handy Whitman Index" was used to adjust cost data from different time periods.

1.4.2 Principal Account Values

As shown in Table 1-3, the total direct costs for the ETF are $327.8 million. With "Engineering and Other Costs", total plant cost for overnight construction at an average ("Middletown") U.S. site, is $362.5 million. Construction in Montana would reduce direct costs by 8 percent.

1.4.3 Confidence Levels

Tolerance on costs, assumed to be a percentage of assigned contingency factors, are:

Contingency %	Tolerance %	Cost Value, $ 10^6
15	10	152.5
20	30	40.8
30	50	134.5

Total worst-case system tolerance is 29 percent, requiring an additional $95 million in direct costs. Corresponding direct and total plant costs are $422.8 and $457.5 million.

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TABLE 1-3

MHD-ETF COST ESTIMATE

Account	Description	Misc Costs	Total Cost, $\$10^6$
310	Land and Land Rights		1.1
311	Structures and Improvements	8.0	31.6
.1	Improvements to Site		6.3
.2	MHD Building		4.5
.3	Turbine and Compressor Buildings		7.7
.4	HR/SR Building		5.2
312	Boiler Plant Equipment	9.8	80.4
.1	Coal Handling and Processing		13.7
.2	Slag and Ash Handling		2.1
.3	Steam Generator (Includes Account 312.4)		36.4
.5	Effluent Control		13.3
.6	Auxiliary Boiler Systems		5.1
313	Engines and Engine Driven Generators		0.0
314	Turbogenerator Units	1.4	30.7
.1	Steam Turbine Generator		14.7
.2	Condenser and Auxiliaries		2.1
.3	Circulating Water System		7.2
.4	Steam Piping		5.3
315	Electrical Systems and Equipment	14.0	31.9
.1	Low Voltage Equipment		4.6
.2	Medium Voltage Equipment		2.3
.3	Control Equipment		11.0
316	Miscellaneous Power Plant Equipment		6.1
317	MHD Topping Cycle Equipment		140.9
.1	Combustion Equipment		23.4
.2	MHD Generator		11.1
.3	Magnet System		53.5
.4	Electrical Consolidation and Inversion		11.1
.5	Oxidant Supply System		11.4
.6	Seed System		9.3
.7	Air Separation Unit		21.1
318	Special Diagnostic Equipment		0.0
319	Performance Evaluation Equipment		0.0
350	Transmission Plant		5.1
	Subtotal Direct Costs		327.8
	Engineering and Other Costs		34.7
	Total (Overnight Construction)		362.5

1.5 SCHEDULES

The schedule organizes all tasks, from inception of design to operation as a commercial facility, into phases of:

1. Preliminary design (DOE Title I)
2. Definitive design (DOE Title II)
3. Procurement, Fabrication, and Construction
4. Testing (checkout)
5. Operations

The two stages of design cumulatively require 50 months. Preliminary design requires 30 months, but the early stages of definitive design are initiated prior to its conclusion. Design is preceded by an additional (minus) year for site activities and an environmental impact analysis.

The boiler assembly, turbine generator, combustor, channel, magnet, and inverter transformers are major items for procurement, fabrication, and construction. The plant becomes operational at month 79, after 11 months of coordinated checkout.

Test operation proceeds for 2 1/2 years, beginning with six months of short duration runs at loads progressing up to base load, and followed by two years of operational testing, including run durations of at least 2,000 hours. Commercial operation is then initiated and continues for 27 1/2 years.

1.6 ISSUES

In the course of preparing the design, the schedule required that a number of decisions be made with only a cursory study of the various alternatives which meet the basic requirements. These were recorded as "issues" to be reviewed after the completion of the design. The selected options and their alternatives include:

1. Seed reprocessing is performed off-site, rather than by constructing a reprocessing facility within the ETF plant site.

2. The MHD channel is accessed for service and replacement by breaking flow train connections and rolling the magnet asembly aside as a single unit. The alternative is to remove the diffuser and transition sections.

3. A high efficiency subsonic channel was selected over the less critical supersonic design.

4. The compressors and plant auxiliaries are driven by steam turbines. Preliminary studies by GAI indicate that the use of electric motors may simplify the design and increase efficiency.

5. The MHD channel is directly cooled by low pressure boiler feedwater. An isolated cooling loop for this system would simplify maintenance.

6. Power is not generated in the fringe magnetic fields at the entrance and exit of the channel.

7. Flue gas was selected over nitrogen for drying the coal.

Several design options were not incorporated because they required components that are not under active development by DOE or were not available during the preparation of the design. These include:

1. The design of the channel to provide a uniform electrode current distribution and thereby greatly simplify the current consolidation network and the inverters.

2. The use of regenerative cooling of the combustor by the incoming oxidant, therby eliminating the oxidant heater in the HR/SR and generally simplifying the plant.

3. The use of a split magnet design whose halves could be rolled apart to expose the channel for inspection and maintenance. The design may also reduce cost by reducing the required size of the warm bore.

The developmental component designs used in the ETF design are typical of those under consideration. The final selection will ultimately be resolved by progress in the MHD Development Program.